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Influence of ultrasonic vibration on the shear formability of metallic materials

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ABSTRACT

The flow stress reduction of metallic materials due to superimposed ultrasonic vibration is an intensively researched phenomenon. So far, however, only a few studies have analysed the vibrational influence on forming limits. Existing findings are inconsistent, suggesting both a formability extension and a decrease. Ultrasonic-assisted shear tests constitute a novel experimental approach for the fundamental investigation of predominant cause–effect–relationships. The test results reveal a distinct correlation between the application of ultrasonic vibration and earlier material failure. This effect is attributed to enhanced crack initiation and propagation caused by localised stress and strain concentration as well as intermittent high strain rates.

1. Introduction and state of the art

Due to the ongoing trend towards mass reduction in the automotive and aerospace industry, modern lightweight materials, such as high strength steel and aluminium alloys, are increasingly applied in cold forming. Rising process forces and limited material formability are interrelated consequences that present challenges for conventional forming technologies [1]. An approach that permits substantial force reduction is the superposition of mechanical tool vibrations in the ultrasonic range during conventional forming operations [2]. Previous investigations in this research field mainly focused on the identification of relevant process influences as well as the involved mechanical [3], tribological [4] and material-related [5] mechanisms leading to oscillation-induced material softening. Even though it is commonly presumed that tool oscillations facilitate the extension of forming limits [6], detailed research concerning vibrational impact on material formability is limited.

Schmauder and Siegert [7] conducted torsion tests with superimposed longitudinal 22 kHz oscillations, oriented perpendicular to the shear plane. The findings suggest a material-dependent influence on the achievable torsion angle. While the fracture limit of steel could be extended, a slight reduction appeared for aluminium. Apart from Schmauder's research work, the connection between ultrasonic vibration and material failure was not systematically analysed. However, the dependency itself was occasionally observed while investigating the material flow behaviour in ultrasonic-assisted tension tests with oscillation frequencies between 15 kHz and 22 kHz. Nerubai [8] reported a fracture strain reduction due to vibration for different high strength steels and titanium alloys. Wen et al. [9] identified a similar impact for magnesium and oscillation amplitudes above 1.5 μm. In tests with lower amplitudes, a fracture strain increase was reached.

Considering the partly opposing results and the limited amount of investigated materials, it is still not known, whether superimposed vibrations influence the forming limits of metallic materials. Further research is therefore necessary. Within this contribution, a suitable experimental procedure allowing the systematic assessment of vibrational influence on material failure under homogeneous shear loading and the identification of underlying mechanisms is developed and applied.

2. Experimental procedure and scope of the investigation

Simple shear tests, adopted from high-speed testing of bulk material [10], constitute a promising experimental design for the fundamental investigation of the vibrational impact on material formability. Different from the torsion tests of Schmauder, the stress state in the shear plane is fairly homogeneous for this type of experiment. The detailed specimen geometry, defining the later shear characteristics, is initially selected based on related literature. An existing test setup for ultrasonic-assisted compression testing is then adapted, to enable both conventional (CST) and ultrasonic-assisted shear testing (USST). Furthermore, a suitable method for failure determination is developed. In this context, material formability is delimited by the displacement, where failure in form of crack initiation occurs. Displacement instead of strain is used for fracture characterisation due to the lack of a reliable way to measure strain under ultrasonic conditions. After experimental testing, the prevailing forming limits are evaluated by examination of the force progression and by metallographic analysis of the crack behaviour. This step is followed by the identification of relevant process influences. Finally,

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the interaction between ultrasonic vibration and material formability is assessed based on the obtained findings.

In this study, conventional and ultrasonic-assisted shear tests with longitudinal vibrations are carried out on stainless steel X17CrNi16-2, mild steel S235JR and cast aluminium AC-43400. During testing, the tool oscillations and the shear plane are oriented in identical direction. To permit the analysis of essential process influences, two different oscillation amplitudes and press velocities are tested. Experiments with three valid repetitions are realised for each parameter combination.

3. Ultrasonic-assisted shear tests

3.1. Specimen geometry and experimental setup

The shear tests are carried out with a tool setup previously developed for ultrasonic-assisted compression tests [11]. In order to realise a homogeneous shear condition by uniaxial compression loading, an appropriate specimen geometry is necessary. Hat-shaped specimens, known from high strain rate shear testing [10], fulfil those requirements. The specimens used in this study (see Fig. 1) are therefore based on this geometry. To allow high geometrical accuracy, mirror symmetric samples are cut from bulk material with an AgieCharmilles CUT2000 wire EDM machine. Identical 10.0 mm long, 0.1 mm wide and 1.0 mm high shear zones are generated on the left and right side.

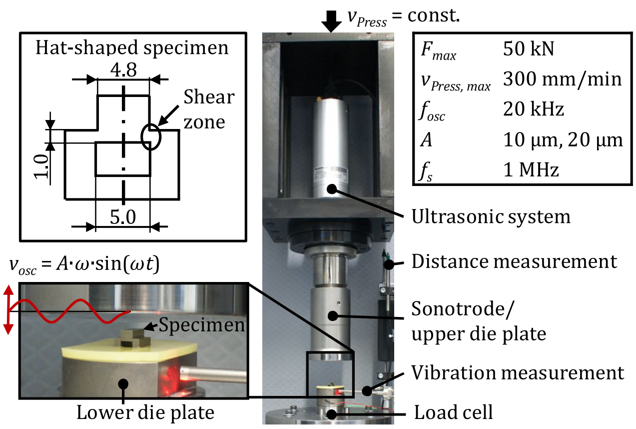

Fig. 1. Specimen geometry and experimental setup.

The used experimental tool setup is also illustrated in Fig. 1. An ultrasonic system with 20 kHz oscillation frequency f_{osc} and 10 µm and 20 µm oscillation amplitude A is integrated into the upper tool part, which is attached to the traverse of a universal testing machine Walter + Bai LFEM 300. The maximum loading capacity F_{max} of the system is 50 kN. During shear testing, the upper tool is moving with constant press velocity v_{Press} of 30 mm/min and 300 mm/min. In addition, a vibrating motion with v_{osc} is superimposed at the sonotrode, which also represents the upper die plate. The forming velocities and the vibration frequency have been selected with respect to typical magnitudes used in industrial operations. Specimens are positioned on the lower die plate in the centre of the lower tool part. Underneath the lower die plate, a piezo-based load cell Kistler 9061A is installed to allow high precision force measurements close to the forming zone. Since load cells show a frequency-dependent transfer behaviour in the high-frequency range, oscillatory forces are calibrated using a previously developed method [12]. The global displacement is measured with length gauges at the upper tool. In order to ensure constant testing conditions, the tool oscillation is monitored by means of a Laser Doppler Vibrometer Polytec OFV-551. A sampling rate f_s of 1 MHz is used to achieve high temporal resolution and avoid aliasing effects.

3.2. Determination of material failure

A typical force–displacement measurement obtained during ultrasonic-assisted shear testing is shown in Fig. 2. After the linear

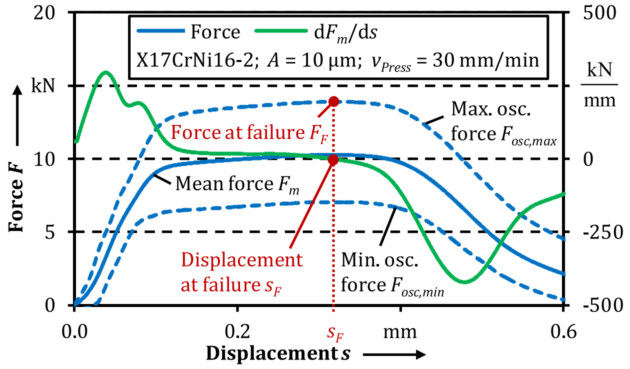

Fig. 2. Determination of material failure.

force increase, a phase with plastic shear deformation appears. This phase ends with material failure and force decline. Due to the oscillating process characteristic, the forming force continually alternates between a maximum $F_{osc,max}$ and a minimum $F_{osc,min}$ oscillatory force. The mean forming force F_m corresponds to the quasi-static force progression. In consequence of the dynamic force calibration, it is possible to analyse vibration-based force reductions and the force at failure, based on the maximum oscillatory force. The evaluation of $F_{osc,max}$ instead of the commonly used mean force is considered to be more suitable, since it provides information regarding the actual maximum specimen loading. During conventional shear tests, $F_{osc,max}$ is equivalent to F_m.

A well-known challenge arising in various types of failure analyses is the appropriate determination of failure initiation on the basis of force–displacement measurements. Moderate curve gradients in combination with occasional signal overshoots and a high sampling rate hinder the reliable automated identification via the maximum process force during ultrasonic-assisted shear testing. Material failure, characterised by the displacement at failure s_F, is therefore determined by the zero position of the gradient dF_m/ds. The corresponding maximum oscillatory force $F_{osc,max}(s_F)$ constitutes the respective force at failure F_F.

4. Experimental results and identified process influences

4.1. Process force and material failure

In the following section, a detailed comparison between conventional and ultrasonic-assisted shear tests with 10 µm and 20 µm oscillation amplitude as well as 30 mm/min and 300 mm/min press velocity is exemplarily presented for stainless steel X17CrNi16-2. The resulting progression of $F_{osc,max}$ for v_{Press} = 30 mm/min is illustrated in Fig. 3a. Related to the conventional tests, an amplitude-dependent force reduction, which is up to ten times higher for A = 20 µm than for A = 10 µm, is achieved by ultrasonic vibration. In addition, earlier shear fracture occurs during ultrasonic-assisted experiments. A similar material behaviour appears for v_{Press} = 300 mm/min (see Fig. 3b).

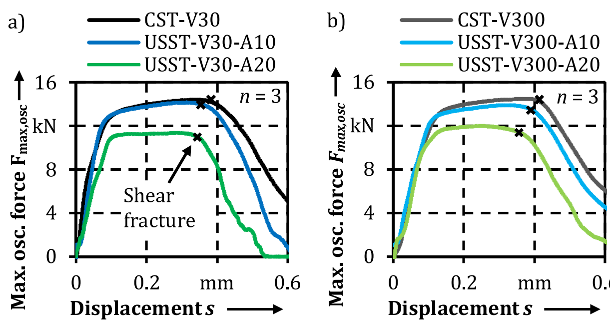

Fig. 3. Progression of maximum oscillatory force during CST and USST with X17CrNi16-2: (a) v_{Press} = 30 mm/min, (b) v_{Press} = 300 mm/min.

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